AD-A182 430 CHARACTERISTICS OF PLANAR OPTICAL WAVEGUIDES FABRICATED 1/1
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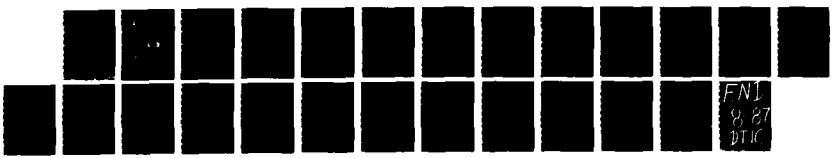

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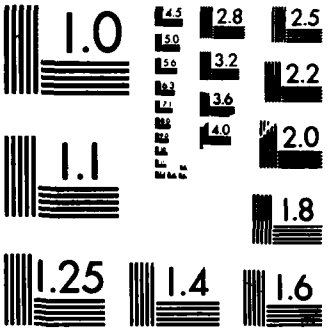

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TECHNICAL REPORT RD-RE-86-4

CHARACTERISTICS OF PLANAR OPTICAL WAVEGUIDES FABRICATED BY SODIUM-SILVER ION EXCHANGE

Robert L. Morgan
George F. Lehnigk
Research Directorate
Research, Development, and Engineering Center

JULY 1986

U.S. ARMY MISSILE COMMAND
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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188
Exp. Date: Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION
Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Cleared for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
RD-RE-86-4

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
Commander
U. S. Army Missile Command

6b. OFFICE SYMBOL (If applicable)
AMSMI-RD-RE

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS (City, State, and ZIP Code)
Redstone Arsenal, AL 35898-5248

7b. ADDRESS (City, State, and ZIP Code)

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL (If applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State, and ZIP Code)

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)
Characteristics of Planar Optical Waveguides Fabricated by Sodium-Silver Ion Exchange

12. PERSONAL AUTHOR(S)
Morgan, Robert L. and Lehnigk, George F.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Summary	FROM 7/85 TO 11/85	JULY 1986	24

16. SUPPLEMENTARY NOTATION
None

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Optics, Waveguide, Dielectric, Planar

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Experimental optical waveguides were produced by ion diffusion from an $AgNO3/NaNO_3$ solution at 300°C. By careful measurement diffusion time, mode number data was developed, which will be useful in the construction of tapered optical waveguide matching sections. These matching sections will be used between laser diode sources and optical modulators.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL
Robert L. Morgan

22b. TELEPHONE (Include Area Code)
205-876-3820

22c. OFFICE SYMBOL
AMSMI-RD-RE

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

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I. INTRODUCTION

The planar optical waveguide is the simplest form to study the phenomenon of optically guided waves since it is essentially a one-dimensional waveguide with the depth of the guiding layer being the only parameter of importance. The y direction is of essentially infinite extent in this guide. The z direction represents the direction of propagation of the transmitted ray and the x direction represents the thickness of the guiding layer.

This report outlines a diffusion method for heavy ion implantation into soda lime glass slides and gives the necessary information and procedure which one must follow in order to produce guides which have only a single spatial propagation mode allowed. Single mode propagation is desired since multimode propagation leads to a time dispersion of phase fronts, thereby limiting the high frequency information transfer limit of the guide.

These studies have been done as preliminary studies to the development of two-dimensional optical waveguides of rectangular or elliptical cross section and transitional tapering in the direction of propagation. The desired end result is to develop a model for glass waveguide couplers which can be used as interfaces between infrared laser diodes and $LiNbO_x$ multichannel optical index modulators and eventually, a high information rate communicators/ computer systems.

Greater detail on the modeling of these planar waveguides as well as accurate measurements of the effective channel index and thickness of the guiding layer will be covered in a report to be published later. Other means of ion implantation into the guide substrate than the diffusion process outlined in this report will also be covered in this later report.

II. FABRICATION AND OPTICAL MEASUREMENTS

A. Ion Exchange Waveguide Fabrication

1. General Process

It is possible to produce planar optical waveguides in soda lime glass substrate by utilizing silver-sodium ion exchange techniques. The production process consists of the following four steps:

a. Preparing and heating an appropriate silver-sodium nitrate solution.

b. Cleaning microscope slides to be used as waveguide substrate.

c. Allowing silver ions to diffuse into a waveguide substrate by floating the glass on the heated solution for a certain duration of time.

d. Removing the substrate from the solution and rinsing. These steps are described in greater detail in the folowing paragraphs.

2. Preparation of a Silver-Sodium Solution

Good results were obtained with a solution consisting of silver nitrate ($AgNO_3$) crystals and sodium nitrate crystals ($NaBO_3$). Sodium nitrate was poured into a clean, dry porcelain dish, capable of withstanding high temperatures (approximately 450 °C) (300.0 g was generally used). For discussion of amounts and concentration see paragraph B below.

Silver nitrate crystals were then weighed and sprinkled onto the sodium nitrate crystals. (Again, the amount may be varied; but amounts between 0.2 g and 0.8 g are recommended for producing waveguides with less than four modes).

The dish was then covered with aluminum foil (to prevent spattering during heating) and placed in a laboratory oven capable of sustaining temperatures of up to 450 °C. The temperature of the sodium-silver diffusion bath may be varied, but a temperature of 350 °C is sufficient for melting the crystals in the dish and producing single-mode and multimode waveguides. When the chemicals have liquefied (approximately 2 1/2 hours at 350 °C, the aluminum foil can be removed and waveguide production begun. It is recommended that the diffusion bath be stirred periodically, between producing waveguides but not during the production process, to ensure a uniform distribution of silver in the solution.

3. Substrate and Cleaning Procedure

Plain microscope slides are adequate for use as waveguide substrates for the ion exchange production techniques.

The surface of the glass substrate must be sufficiently clean to allow silver ions to migrate uniformly into the glass substrates. The surface that comes in contact with the solution, therefore, must be dry and free of dirt or lint. This can be achieved by first washing the slide in a distilled water/detergent mixture with a cotton swab, and then rinsing the slide thoroughly with distilled water. The glass slide is dried best by using a stream of nitrogen gas.

More thorough cleaning procedures, involving ultrasonic devices and isopropyl alcohol, had no effect on the quality of the waveguides produced. It was found that glass slides, visibly free from dust and stains, produced good results and that excessive cleaning procedures are unnecessary.

4. Diffusion Process

The microscope slides are best lowered onto the diffusion bath by means of a crampon fashioned from tungsten wire rather than by means of tweezers. A wire crampon is recommended, since it allows one to gently place the glass slide on the solution's surface and remove it from the solution. Using tweezers increases the likelihood of having the glass sink into the diffusion bath; a situation which should be avoided, since it is desired that the silver ions diffuse into the glass from only one side. The wire crampon can remain attached to the floating substrate while ion diffusion is taking place, since it does not interfere with the diffusion process.

Care should be exercised in preventing sharp temperature variations in the oven during the diffusion process. Thus, the glass slides should be placed onto the bath as quickly as possible, allowing a minimum of heat to escape from the oven. This is essential if one wishes to reliably produce waveguides with a specified number of modes: mode number is strongly temperature dependent (see paragraph B below), and thus, relatively small uncertainties in temperature can lead to significant uncertainties in mode number.

The diffusion time varies from seconds to hours and is determined by the number of modes desired. Typical diffusion times required for producing single-mode waveguides ranges from 30 seconds to 7 minutes, the exact time depending upon the silver concentration in the bath and the temperature of the bath. The graphs in Figures 1 through 4 can be used to determine the appropriate silver concentration, solution temperature, and diffusion time for producing waveguides of a specific number of modes.

5. Removal and Final Rinse

The glass substrate should be removed 2 to 5 seconds before the desired diffusion time has expired. Since the $AgNO_3$ + $NaNO_3$ solution clinging to the bottom of the glass slide does not crystalize immediately after removal from the bath, therefore the diffusion process continues for those moments before crystalization occurs.

The crystalized solution is most easily removed by placing the glass slide in distilled water and brushing the surface lightly with a cotton swab. Before placing the slide in water, however, one must allow it to cool sufficiently in air, so that it will not shatter once it touches the water. Adequate cooling time is usually 1 minute. Water may be lightly sprinkled on the slide during this time to speed up the cooling process.

It is good practice to etch the side of the glass, into which the ions diffused, with a diamond scribe immediately after rinsing off the excess solution, so that the diffused side can be distinguished from the undiffused side.

B. The Effects of Diffusion Time, Ion Concentration, and Temperature

1. General Effects

The ability to produce waveguides in glass substrates by diffusing ions into the glass has been documented by several authors. The glass substrates are brought into contact with a heated solution containing, for example, silver ions. These ions then diffuse into the glass, replacing lighter ions originally contained in the glass. This exchange of ions produces a region in the glass which has a higher index of refraction than the regions on either side (air on one side and undiffused glass on the other). Such a glass, with a variable index of refraction, in turn, can function as a waveguide in that it can transport an optical signal by means of modes with very low dB/cm losses.

The larger the variation of the index of refraction, the larger the number of modes will be. Since the value of the refractive index is dependent on the concentration of silver (Ag^+) ions in the diffused region of the substrate, there is also a relation between Ag^+ concentration and mode number. The number of Ag^+ ions, in turn, is a function of the time in the bath, and the temperature of the bath.

2. Mode Number and Diffusion Time

Figure 1 shows a typical dependency of mode number on the diffusion process duration, for a constant bath concentration and temperature. As shown longer diffusion times imply a greater number of modes in the waveguides.

By studying the data of the shorter diffusion times (less than 15 minutes), one can also see that the diffusion time range becomes longer for successive mode numbers. A zero-mode waveguide has a span of approximately 1 minute, a single-mode waveguide has a span of approximately 4 minutes, and a double-mode waveguide has a span of approximately 8 minutes.

It was found that waveguides produced with diffusion times falling just beyond the step regions (i.e., 1.5 minutes, 6.0 minutes, and 15.0 minutes diffusion time in Fig. 1) exhibited a mode that was less pronounced than the others in the same waveguide.

This weakest mode can be said to correspond to the "newly formed" mode and the amount of silver diffused into the substrate can be thought of as "just enough to barely support the new mode." A signal transmitted via the weak mode gains in intensity as soon as the diffusion times approach the center of each range, for example, the 3-minute waveguide exhibits one strong mode and the 12-minute waveguide exhibits two strong modes.

It could not be determined whether very long diffusion times cause the mode number to approach an upper limit, or to return to zero: waveguides supporting both theories were produced. A substrate diffused for 3 hours and 15 minutes produced a waveguide with as many as eight modes. A 5-hour waveguide (same concentration, approximately same temperature) produced what appeared to be one very faint mode. However, since long diffusion times generally produced waveguides with weak modes and very bad resolution, this data is suspect. Thus, a thorough examination of the relationship between mode number and very long diffusion times is warranted.

3. Mode Number and Concentration

Figure 2 illustrates mode number vs diffusion time for three concentrations of silver nitrate (the temperature and the amount of sodium nitrate were held constant).

As should be expected, substrates treated with higher concentrations of silver ions required less diffusion time to produce a waveguide with a specified number of modes. The relationship between silver ion concentration and diffusion time is not a simple inverse relationship, however.

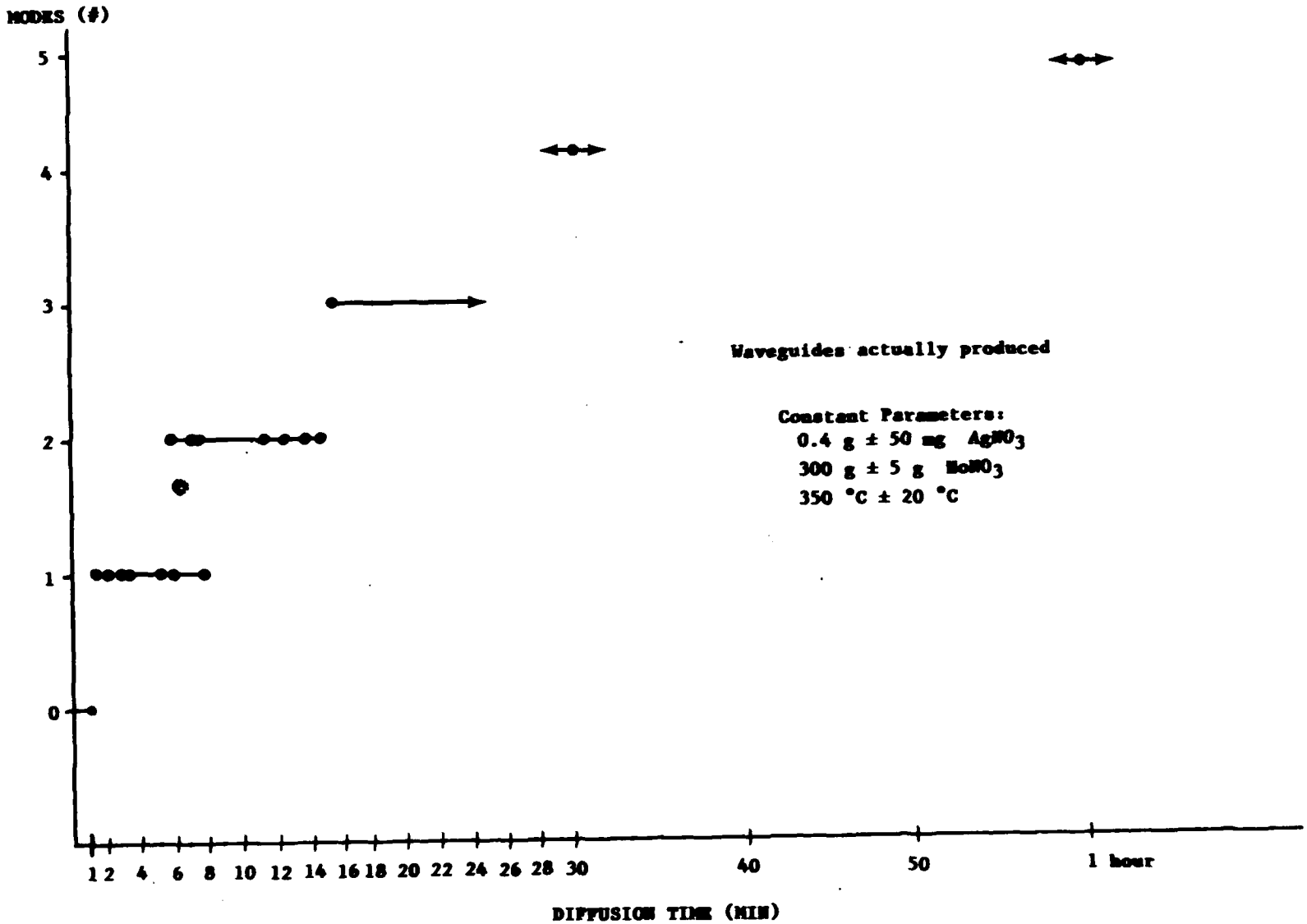

Figure 1. Mode number and diffusion time.

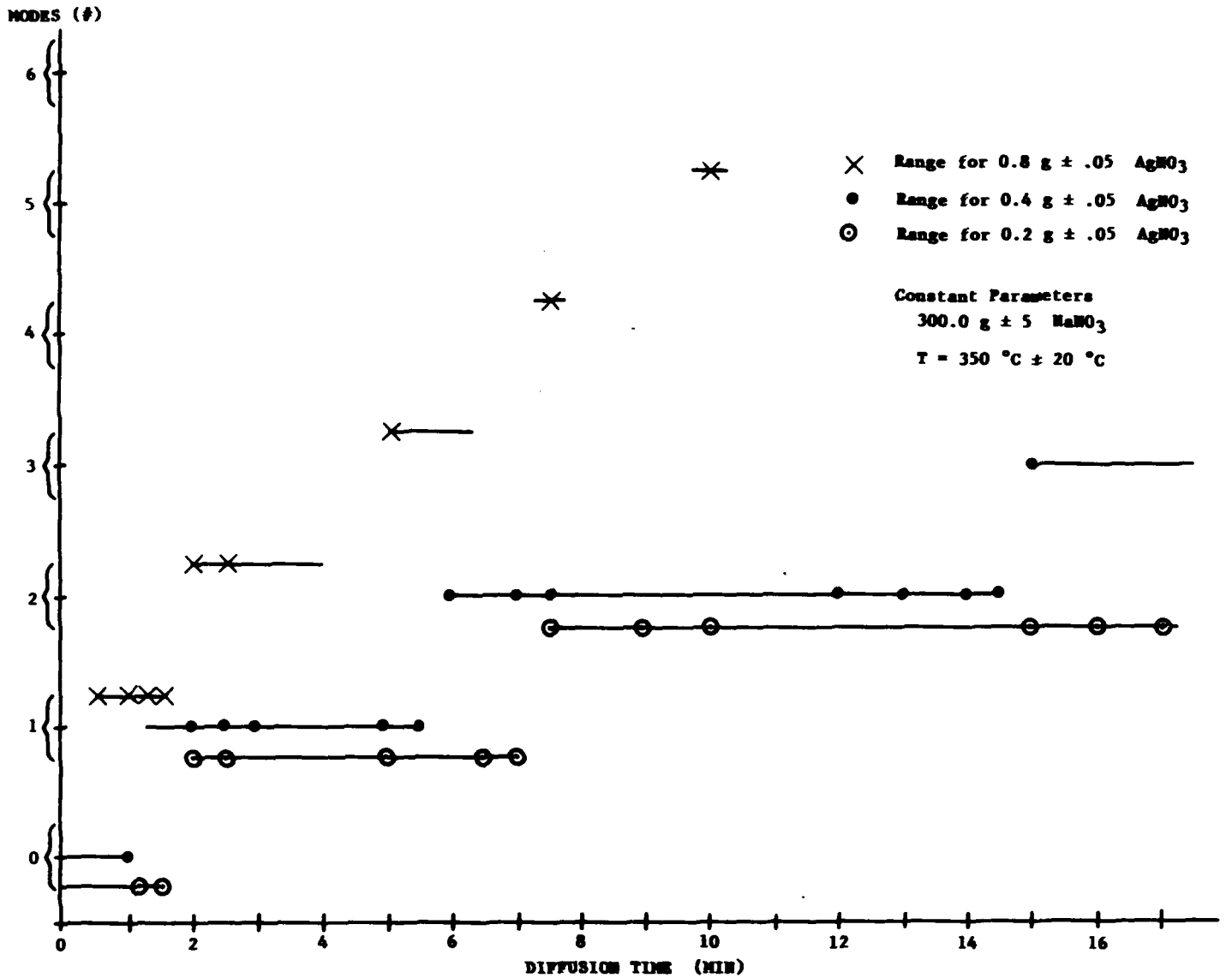

Figure 2. Mode number and concentration.

It was not found, for example, that a 4-minute diffusion time was sufficient to produce a two-mode waveguide using a 0.4 g $AgNO_3$ solution even though 8 minutes would produce a two-mode waveguide using a 0.2 g $AgNO_3$ solution. To determine the exact functional relationship between silver ion concentration and diffusion time, a much larger assortment of waveguides, fabricated with a much greater range of concentrations, would be necessary.

Note that it is the ratio of $AgNO_3$ to $NaNO_3$ (i.e., the concentration) that relates to the diffusion time, and not simply the amount of silver present in the diffusion bath. Figure 3 illustrates this point. A bath containing 0.4 g $AgNO_3$ and 600.0 g $NaNO_3$ gave results comparable to a bath containing 0.2 g $AgNO_3$ and 300.0 g $NaNO_3$ (i.e., the same concentration) rather than comparable to a bath containing 0.4 g $AgNO_3$ and 300.0 g $NaNO_3$ (i.e., the same amount of silver nitrate).

Finally, note that increasing the concentration decreases the range of diffusion time for any given mode number. For example, in order to produce a single-mode waveguide using a 0.4 g $AgNO_3$ + 300.0 g $NaNO_3$ concentration, a diffusion time can be chosen anywhere in the range from 1.25 minutes to 5.5 minutes. If a 0.8 g $AgNO_3$ + 300.0 g $NaNO_3$ solution is used, however, one has a range of from only 30 seconds to 1.5 minutes.

4. Mode Number and Temperature

Figure 4 is a graph showing the number of modes detected in waveguides produced at two different temperatures (the concentrations of the baths used were the same). The results obtained were as expected: that greater temperatures imply greater thermal agitation, which leads to a stronger diffusion of ions into the glass over a given period of time. Thus, expect the jump from (n) modes to (n+1) modes to occur sooner for higher temperatures. This was indeed verified, as shown in the graph.

The dependence of mode number on temperature was much stronger than expected. Increasing the temperature by less than 100 °C (from 350 °C to 440 °C) generally decreased the diffusion time necessary to form a given number of modes by more than one half. For example, increasing the bath temperature from 350 °C to 440 °C cut the lower limit for producing a double-mode waveguide from 6 minutes to 2 minutes.

Finally, increasing the bath temperature has the same effect on the ranges of diffusion time as did increasing the concentration: higher temperatures produced shorter time ranges.

5. Sources of Error

The reader may have noted that gaps of generally 30 seconds exist in most of the graphs at the mode increment points. The increment points were not narrowed down more precisely than 30 seconds, since the various parameters could not be controlled precisely enought to give reliable results in these regions.

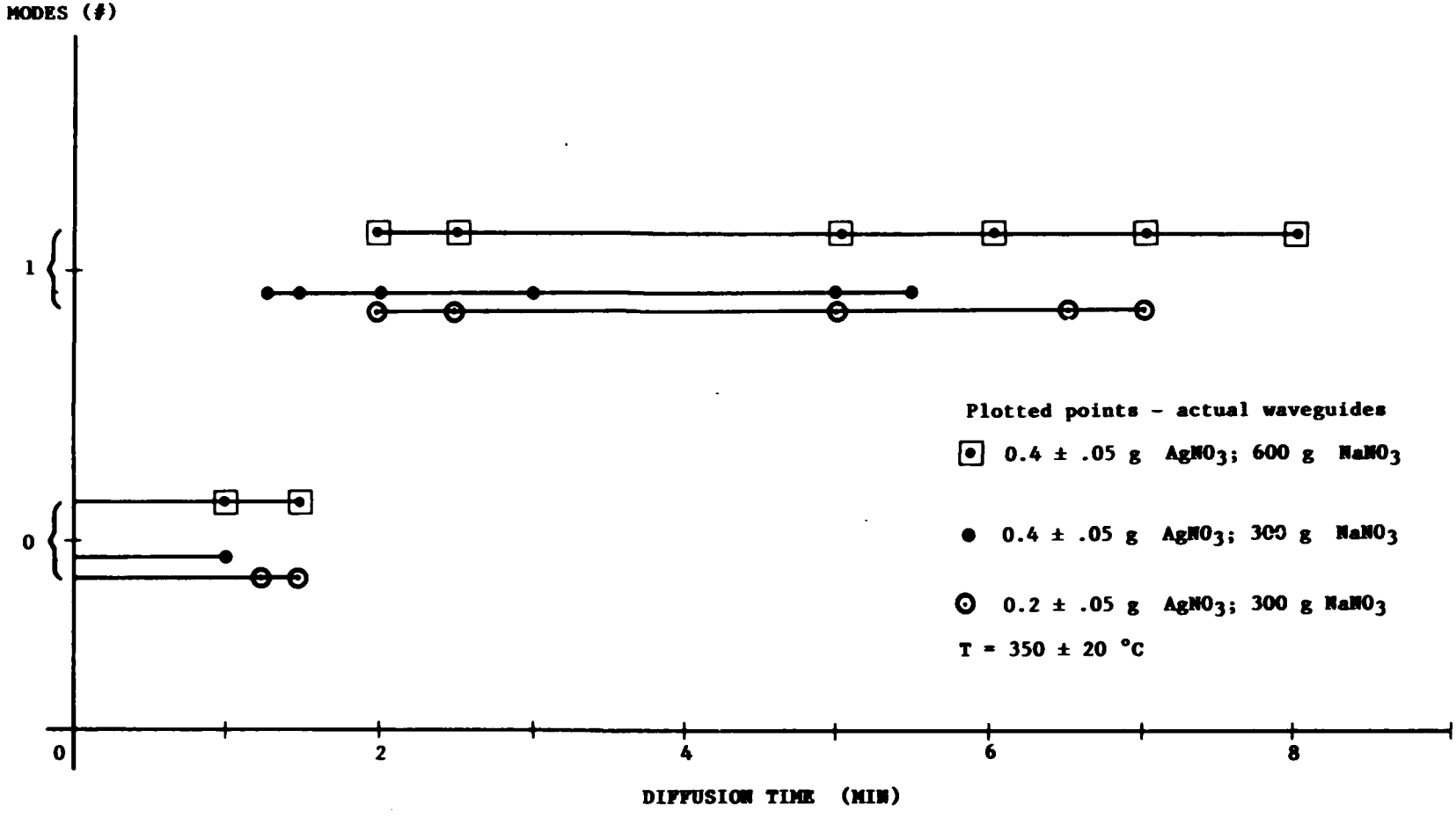

Figure 3. Ratio of concentration and diffusion time.

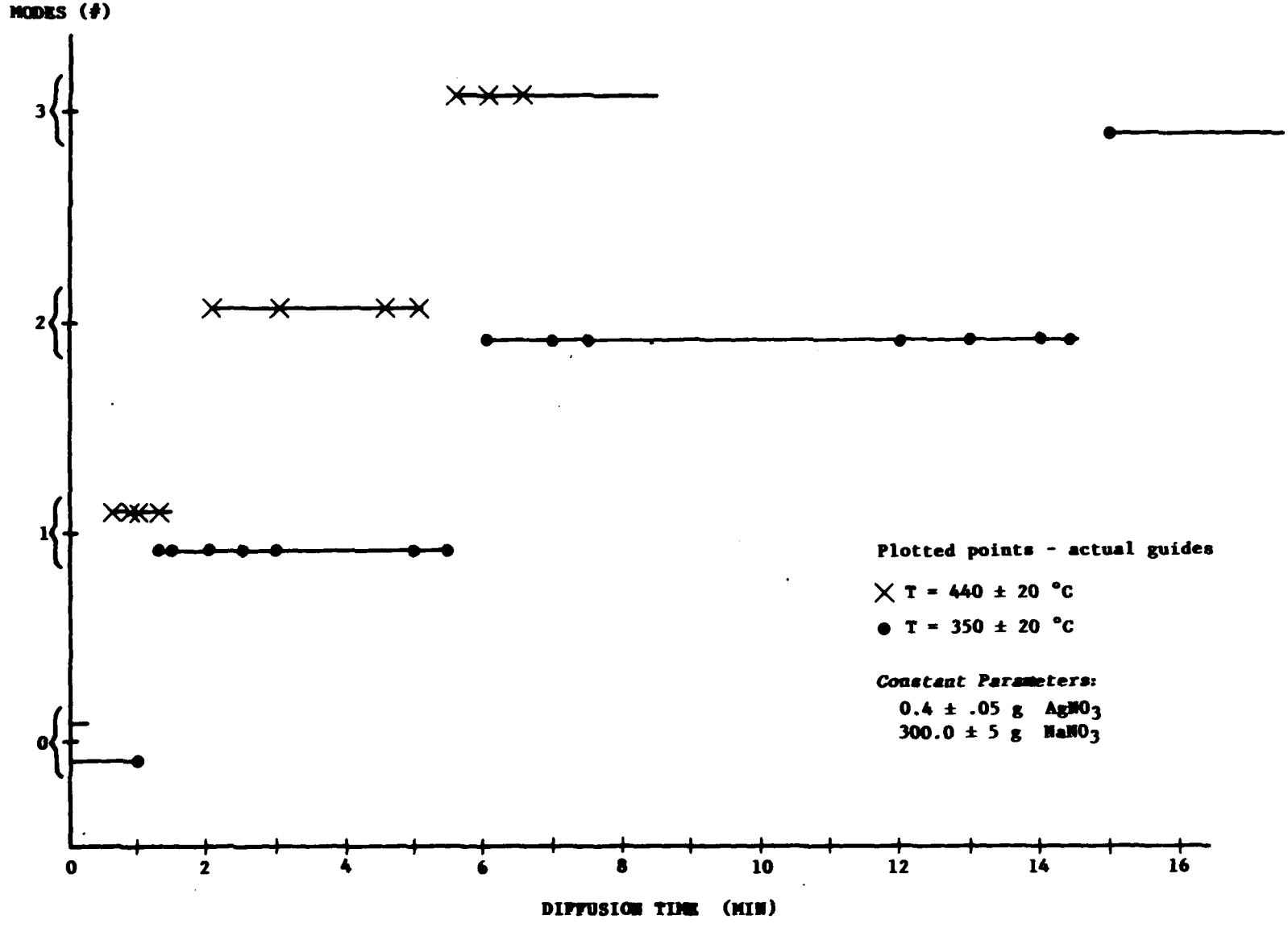

Figure 4. Mode number and temperature.

The actual diffusion times are accurate to within about 10 seconds. This uncertainty in diffusion time exists because it is assumed that diffusion does not stop immediately after removing the substrate from the bath. A certain amount of solution clings to the bottom of the substrate after removal which does not crystalize for several seconds. Thus, diffusion probably still takes place during this period, although at a much reduced rate, since the substrate cools rapidly. It is safe to assume that, once the clinging solution has crystalized, diffusion stops. A small degree of error presumably also stems from inaccuracies in the amounts of silver nitrate and sodium nitrate in the diffusion bath. The initial weighing of the chemicals yielded the following degrees of accuracy:

Sodium nitrate ($NaNO_3$): 300.0 g $\pm$ 0.5 g: 99.83% accuracy

Silver nitrate ($AgNO_3$): 0.4 g $\pm$ 5.0 mg: 98.75% accuracy

However, the same bath was used for entire series of waveguides and the fabrication of each waveguide depleted the bath of slight amounts of $AgNO_3$. If the amounts of the two chemicals that were removed corresponded to the ratio of the chemicals originally in the bath, then no inaccuracies result because mode number is a function of concentration, not total quantity. It is assumed that the ratio of silver to sodium in the bath declined over successive waveguide fabrication sessions, because of the tranferral of silver ions from the bath into the substrate. Thus, the bath is slowly deprived of silver ions, which would eventually lead to inaccuracies large enough to measure.

The most difficult parameter to control was temperature. Placing the glass substrate on the diffusion bath necessitated opening an oven, which allowed heat to escape. This decreased the temperature in the oven by as much as 20 degrees.

As was noted in paragraph 4 above, even relatively small temperature variations had dramatic effects upon the diffusion process. Thus, the estimated uncertainty of $\pm$ 20 °C could shift the minimum diffusion time for a certain number of modes by at least 30 seconds.

6. Single-Mode Waveguides Production

Figures 1 through 4 can be used to determine values for the various parameters when producing single mode or multimode waveguides. It is recommended that diffusion times be chosen to correspond to the middle regions of the diffusion time ranges. First, this ensures that strong modes are produced and second, it maximizes the probability of producing a waveguide with the desired number of modes.

It is also recommended that weak concentrations (approx. 0.2 - 0.4 g $AgNO_3$ with 300.0 g $NaNO_3$) and low temperatures (approx. 350 °C) be used: since the ranges are longer for weak concentrations and for low temperatures, one again maximizes the probability of producing the desired type of waveguide, if one uses such concentrations and temperatures.

7. Miscellaneous Remarks

Data concerning the relative angle of incidence of laser light to the waveguide substrate was recorded in addition to the mode number data discussed above: in all cases, the modes occurred at angles ranging from approximately 30 to 35°. The change in angle (delta theta) between adjacent modes was also recorded.

The more meaningful set of data is believed to be the values of delta theta. The angles recorded are not deemed meaningful, for the following reasons:

a. The angle of incidence was found to depend strongly on the amount of index matching fluid used between the substrate and the prism coupler (delta theta did not display such a dependency).

b. The angle of incidence also depended on how tightly the prism was coupled to the substrate (delta theta was again independent of the coupling strength).

c. It is not certain whether the laser beam coupled into the substrate exactly on the axis of rotation (since delta theta is a relative parameter, it is again unaffected by this source of error). It is estimated that values recorded for coupling angle are accurate to within thirty angular minutes and that values for delta theta are accurate to within 5 minutes.

An unexpected phenomenon was noted which seemed to occur in a random set of waveguides: a faint zig-zag propagation, similar to the propogation characteristic of large incident angles, occurred in various waveguides in the angular region normally devoted to mode propagation. The source of this secondary propagation is unknown and will be investigated further.

It was not determined if the waveguides produced were buried in the substrate or not. Giallorenzi, et al.[1] in their article "Optical Waveguides Formed by Thermal Migration...," claim that waveguides produced by the methods employed here are somewhat buried in the substrate. Thus, it will be determined if the ion-exchange profiles of the waveguides produced correspond to buried or non-buried waveguides.

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[1]Giallorenzi, et al., "Optical Waveguides Formed by Thermal Migration of Ions and Glass," Applied Optics, Vol 12, pp. 1240-1245, 1973.

III. SOME THEORETICAL CONSIDERATIONS

If a slab waveguide of infinite extent in both the y and z directions, as shown in Figure 5, has a thin layer which has a higher index of refraction n_2 than either the uppermost layer n_1 and the substrate layer n_3, then there will be some angle θ_C at which a ray propagating in layer II will be totally reflected. Then at one or more of the angles $\theta \leq \theta_C$, a ray will be found to propagate without destructive phase interference. Thereby, an optically propagating mode will be established which allows the transfer of power from one end of the guide to the other along the x direction.

A mode of a dielectric waveguide at a frequency ω is a solution of the wave equation.

$$\nabla^2 E(r) + k_0^2 n^2(r) E(r) = 0; \text{ where } k_0^2 \equiv \omega^2 \mu \varepsilon_0 = (2\pi/\lambda)^2 \qquad (1)$$

and n is the index of refraction.

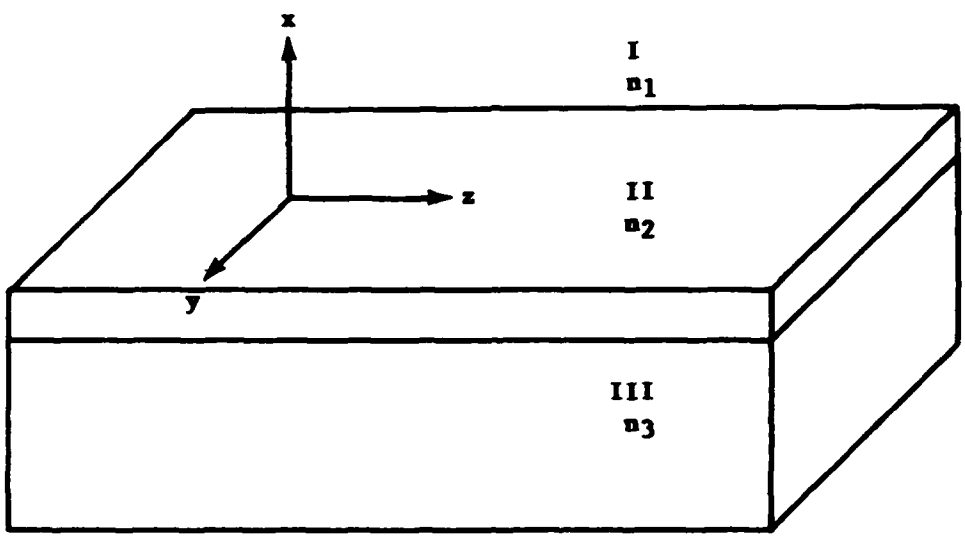

Figure 5. Slab waveguide.

The solutions are subject to the continuity of the tangential components of the E and H field at the dielectric interfaces.

If the form of the field is taken to be

$$E(r,t) = E(x,y)e^{j(\omega t-\beta z)} \tag{2}$$

then Equation (1) becomes

$$(\partial^2/\partial x^2 + \partial^2/\partial y^2)E(x,y) + (k_0^2\, n^2[r] - \beta^2)E(x,y) = 0 \tag{3}$$

The behavior of dielectric waveguides can be seen, more readily, with the help of the slab or planar waveguides in which no variation exists in one of the directions for instance in our case the y direction giving $\partial/\partial y = 0$. Using this simplification and rewriting Equation (3) separately for each of the three regions noted in Figure 5, the following is obtained:

$$(\partial^2/\partial x^2)E(x,y) + (k_0^2\, n_1^2 - \beta^2)E(x,y) = 0\ , \tag{4}$$

$$(\partial^2/\partial x^2)E(x,y) + (k_0^2\, n_2^2 - \beta^2)E(x,y) = 0\ , \tag{5}$$

and

$$(\partial^2/\partial x^2)E(x,y) + (k_0^2\, n_3^2 - \beta^2)E(x,y) = 0 \tag{6}$$

where E(x,y) is a Cartesian component of E(x,y).

Much can be learned about the physical nature of the solution to this boundary value problem by simple arguments. Consider the nature of the solution as a function of the propagation constant B at a fixed frequency ω. Assume that $n_2 > n_3 > n_3$, then for $\beta > k_0 n_2$, it follows directly from Equation (5) that $(1/E)(\partial^2 E/\partial x^2) > 0$ everywhere and E(x) is exponential in all three layers of the waveguide (Fig. 6(a)). Because of E(x) and its derivative at the two interfaces, the resulting field increases without bounds away from the guide. This is not physically possible and does not correspond to a real mode.

For the case $k_0 n_3 < \beta < k_0 n_2$, it follows that the solution is sinusoidal in region II, and since $(1/E)(\partial^2 E/\partial x^2) < 0$ in regions I and III is a decaying exponential, it is possible to have a solution E(x) that satisfies the boundary condition while decaying exponentially in regions I and III.

Two such solutions are shown in Figure 6(b) and (c). As shown, the energy carried by these modes is confined to the vicinity of the guiding layer and can be called guided modes.

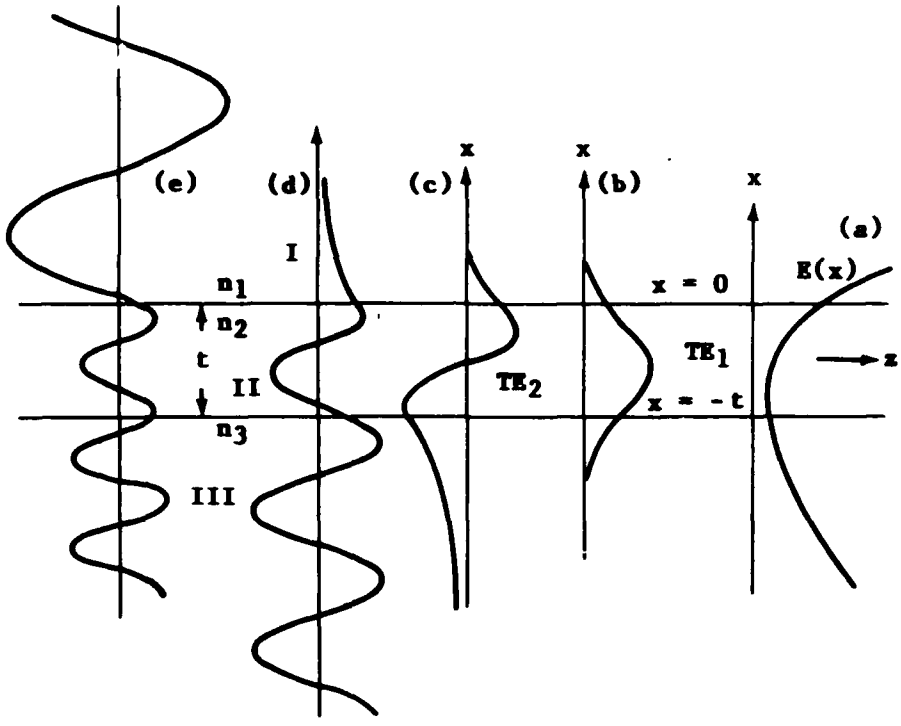

Figure 6. Three-layer waveguide.

For the case $k_0 n_1 < \beta < k_0 n_3$, the solutions correspond to exponential behavior in region I and to sinusoidal behavior in regions II and III. These modes are called the substrate radiation modes (Fig. 6(d)) and result when the injection angles of the interface be-tween regions II and III but has not exceeded the critical angle of the interface between regions I and II.

A report, to be published later, will present a more detailed modeling theory.

IV. CONCLUSION

It has been determined that single mode one-dimensional guides may be prepared, relatively easy, by the ion diffusion process. Further experiments are indicated using alternate ion diffusion methods. It is also indicated that studies should be initiated on the two-dimensional optical waveguides.

The introduction of the y independent variable also introduces the possibility of more propagation modes. To generate single mode two-dimensional guides, it will be necessary to use photolithographic thin film techniques. This is necessary because the lateral (y) dimension of the guide must be of the order of micrometers so that more than one lateral mode is not supported. Ion bombardiment techniques with exposed photoresist will probably be the correct method to effectively manufacture the two-dimensional guides.

The problem of tapered guides adds an additional degree of difficulty, if the tapering must be in the x direction (thickness), since a novel diffusion technique will of necessity have to be developed.

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